Light WIMPs!

Dan Hooper
Fermilab/University of Chicago

SUSY 2011 Workshop
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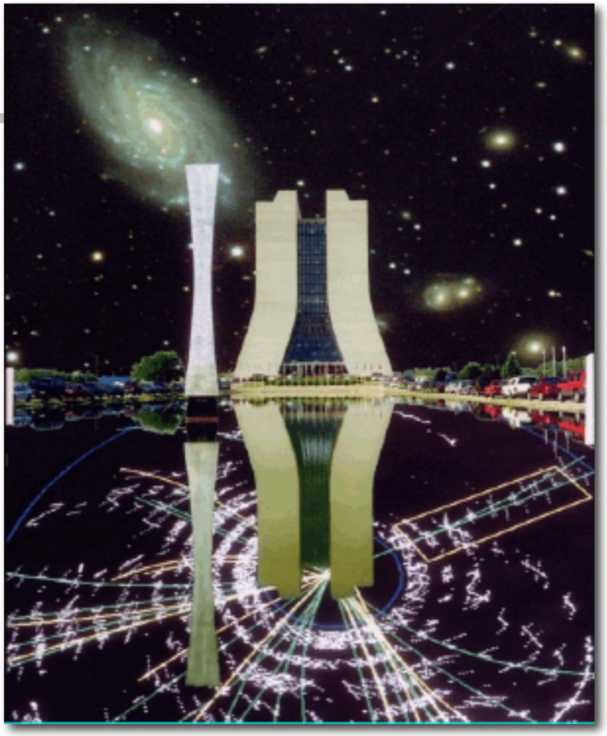

In Defense of Light WIMPs

- The thermal abundance ("WIMP Miracle") argument works roughly equally well for WIMPs with masses between ~1 GeV and several TeV

- Historically, we have focused on ~40 GeV to ~1 TeV WIMPs for a number of reasons (neutralino/chargino mass ratios in minimal supersymmetry models, for example) which do not apply more generally to other dark matter candidates

- Papers have been written, analyses have been carried out, and experiments have been designed (and funded) with this bias in mind

- I know of no compelling argument for why dark matter should not consist of ~1-20 GeV particles

An Empirical Case For 5-10 GeV Dark Matter Particles?

- DAMA/LIBRA, CoGeNT, and CRESST have each reported signals which are inconsistent with known backgrounds, and (roughly) consistent with the elastic scattering of ~5-10 GeV dark matter particles

- The spectrum of gamma rays from the region surrounding the Galactic Center peaks at a few GeV, consistent with a ~7-10 GeV dark matter particle annihilating largely to leptons, with a cross section on the order of that predicted by relic abundance considerations

- The same annihilation rate and channels needed to produce the observed gamma rays from the Galactic Center automatically leads to a synchrotron signal similar to the observed "WMAP Haze", and to the peculiar spectral features observed from the Milky Way's radio filaments

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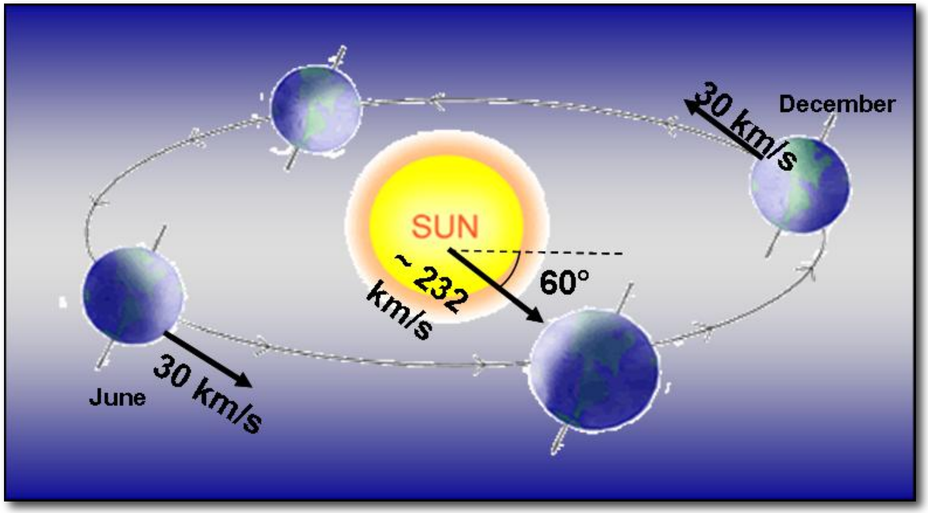
While certainly not a bulletproof case at this point, this body of evidence is quite suggestive, and there exist several ways to potentially confirm or refute this hypothesis in the near future

Signals From Direct Detection

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is predicted to induce a modulation in the dark matter scattering rate



Drukier, Freese, Spergel, PRD (1986)

Signals From Direct Detection

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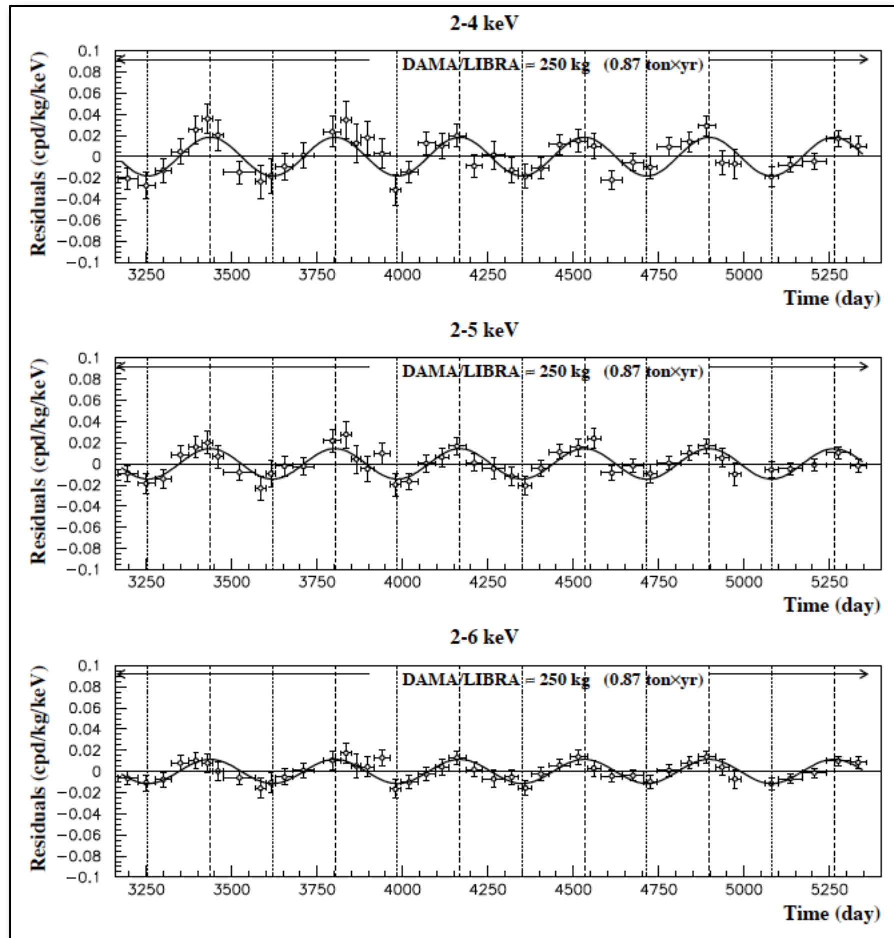
- The DAMA collaboration reports modulation with a phase consistent with dark matter, and with high significance (8.9σ)

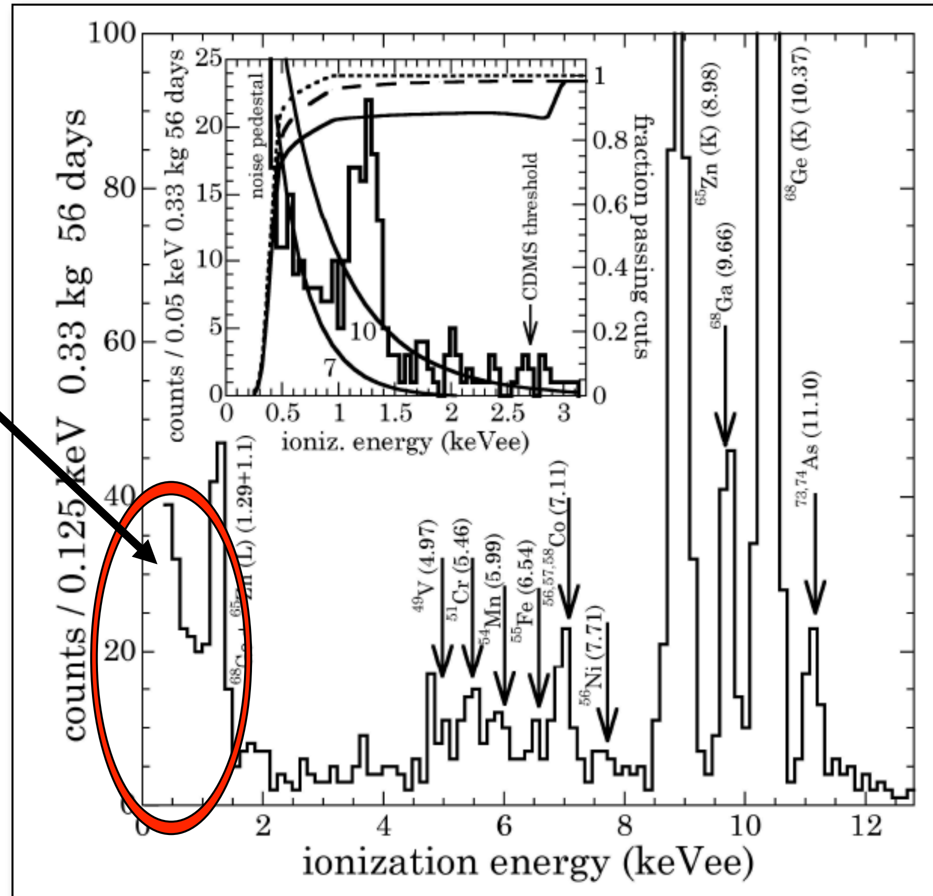


Signals From Direct Detection

CoGeNT

- The CoGeNT collaboration, last year, announced the observation of an excess of low energy events, with a spectrum consistent with that predicted from a 5-10 GeV dark matter particle

- Although it has less exposure than other direct detection experiments, CoGeNT is particularly well suited to look for low energy events (and low mass WIMPs)

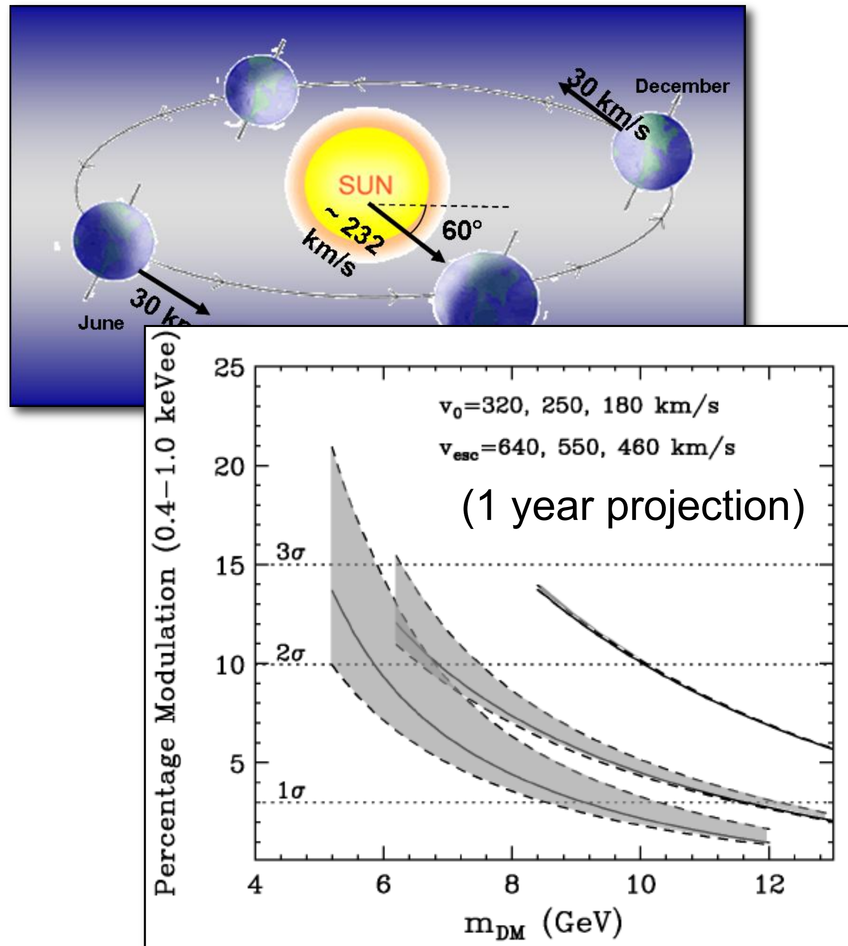


CoGeNT Collaboration, arXiv:1002.4703

The Key Test: An Annual Modulation At CoGeNT

- The originally published CoGeNT excess consisted of ~10^2 events, from winter season (56 days); insufficient to observe any annual variation in rate

- If these events are the result of elastically scattering dark mater, we predicted a ~5-15% annual modulation at CoGeNT (10-30% higher rate in summer than in winter)

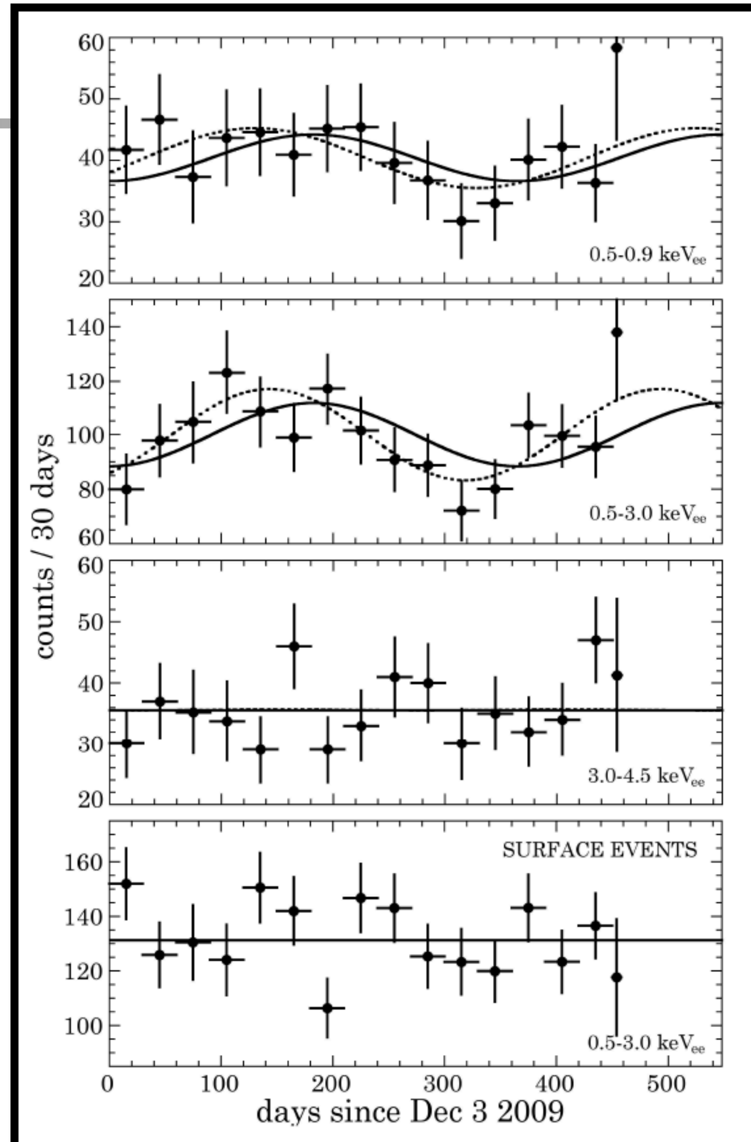


Kelso, Hooper, arXiv:1011.3076; Hooper, Collar, Hall, McKinsey, PRD, arXiv:1007.1005

Annual Modulation at CoGeNT

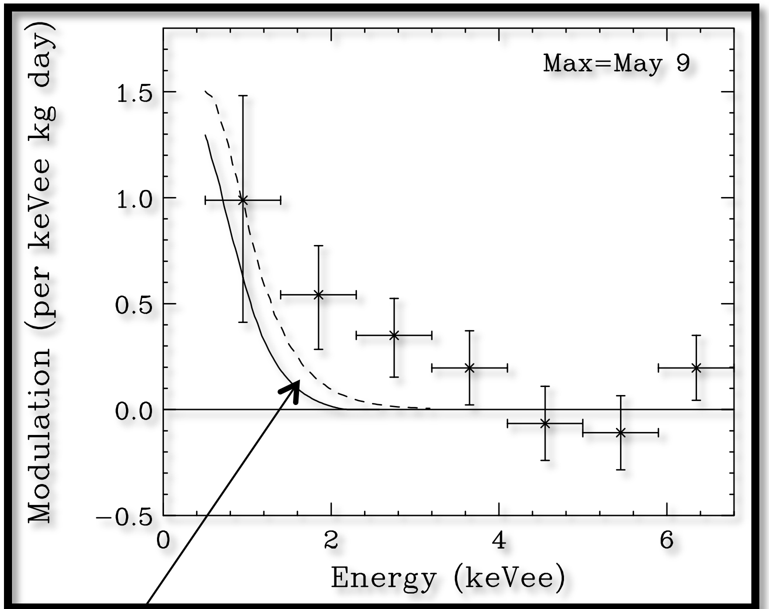
- In CoGeNT's recent 15 month data release, modest evidence for modulation does appear; favored over the null hypothesis at 2.8σ (99.4% CL)

- Observed amplitude (16.6±3.8%), phase (347±29 days), and period (maximum at April 16±12) are consistent with expectations from a light, elastically scattering dark matter particle (and with DAMA/LIBRA's modulation)



Annual Modulation at CoGeNT

- In one respect, CoGeNT's modulation does not look particularly like that predicted by dark matter – more modulation is observed at higher energies that would be anticipated based on the overall spectrum



Hooper and Kelso, arXiv:1106.1066

Prediction based on spectrum

Annual Modulation at CoGeNT

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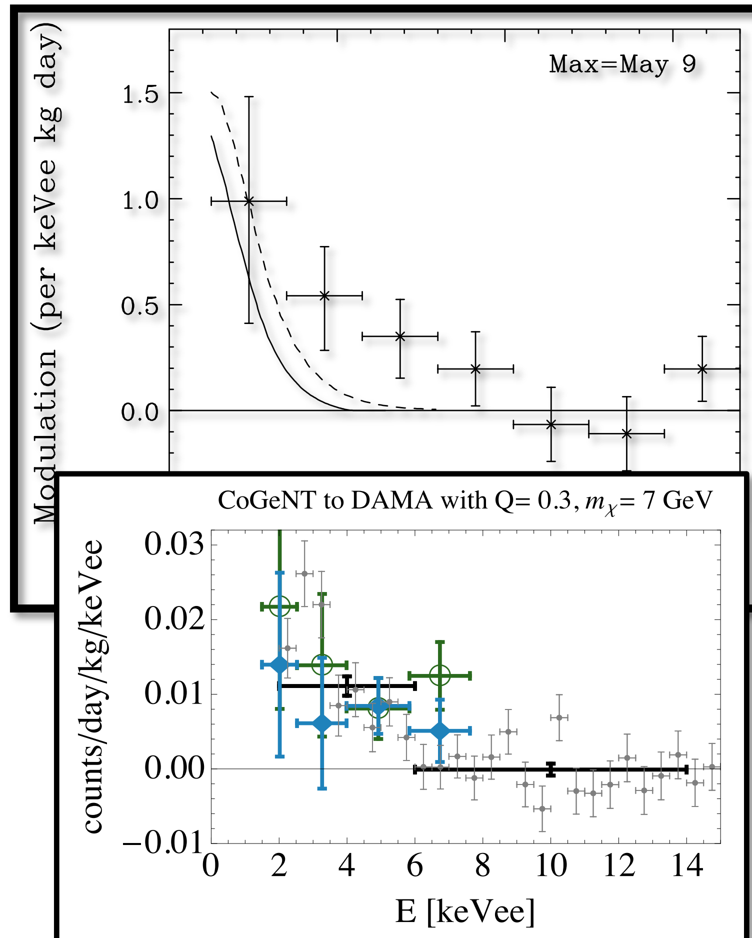
- This could be the result of limited statistics and go away with more data (although the agreement between CoGeNT and DAMA suggests otherwise)



Fox, Kopp, Lisanti, Weiner arXiv:1107.0717

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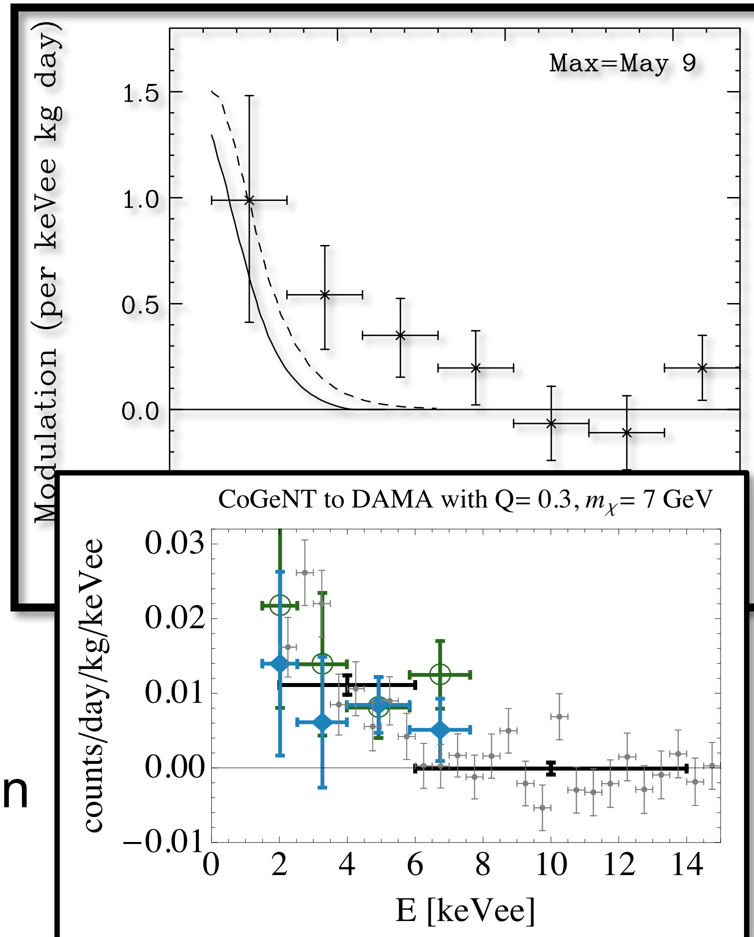
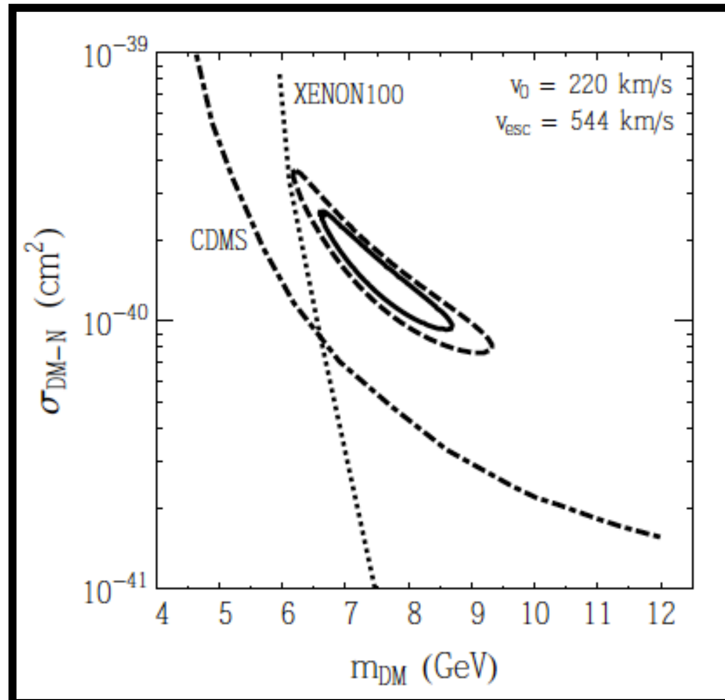
- This could also originate from non-maxwellian velocity structure (a small fraction of the dark matter distribution in streams, for example)



Fox, Kopp, Lisanti, Weiner arXiv:1107.0717

Consistency With CDMS, XENON100

- The recent low threshold analysis by CDMS claims to be in tension with this interpretation, as do the recent constraints from XENON100

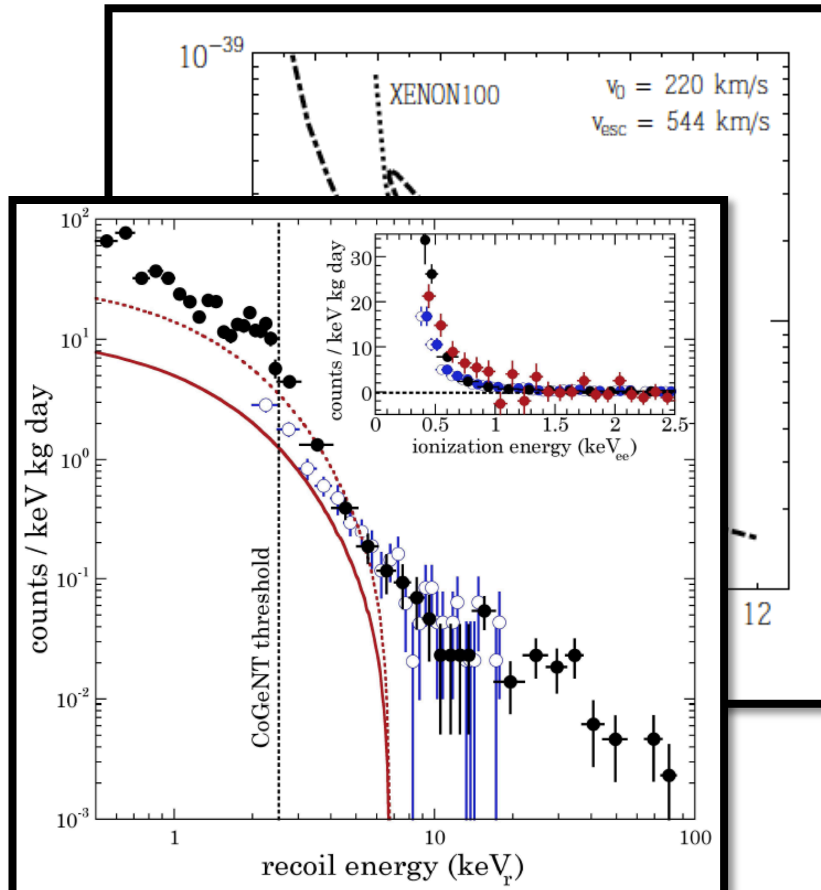


Consistency With CDMS

- The lack of excess events in the CDMS spectrum is difficult to reconcile with a dark matter interpretation of CoGeNT – both CDMS and CoGeNT use germanium targets

- The event spectrum reported by CDMS, however, is not all that different from that observed by CoGeNT – it is not implausible that systematic uncertainties (in both experiments) could bring these results into consistency with one another

- If CoGeNT is seeing dark matter, then CDMS's low energy spectrum should contain significant modulation



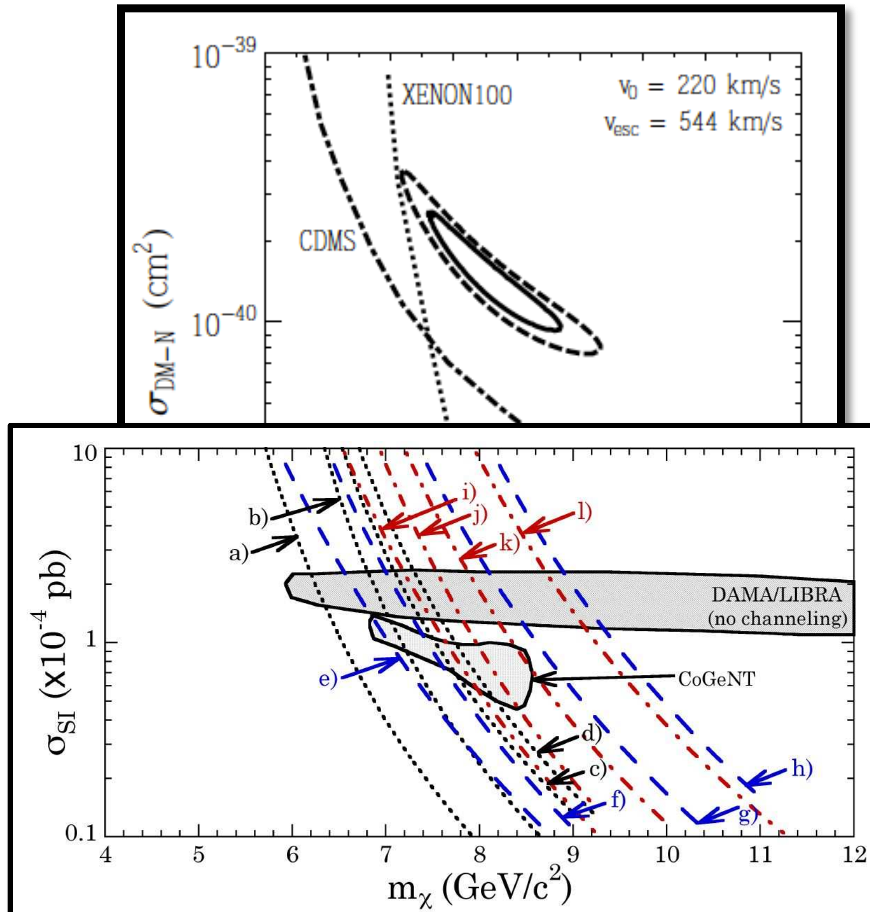
J. Collar arXiv:1103.3481

Consistency With XENON

- While the results of XENON100 (and XENON10) claim to exclude the CoGeNT region, this conclusion depends sensitively on the response of liquid xenon to very low energy recoils (L_{eff}, Q_y)

- Furthermore, if dark matter particles possess different couplings to protons and neutrons, the sensitivity of xenon-based experiments could be reduced

- My opinion: If all systematic uncertainties (associated with CoGeNT, XENON, CDMS, velocity distributions, etc.) were properly taken into account, a consistent picture could plausibly appear



J. Collar arXiv:1106.0653

Signals in Other Experiments?

CRESST

- In recent talks by members of the CRESST collaboration, a 4.6σ excess over known backgrounds has been reported (paper expected soon)
- The excess events appear in the oxygen band, implying a low WIMP mass
- The best fit point was reported to be m=13 GeV, with σ=3x10^{-40} cm^2, although these values are likely to be surrounded by considerable error bars
- Official results and corresponding paper are planned for TAUP meeting in September

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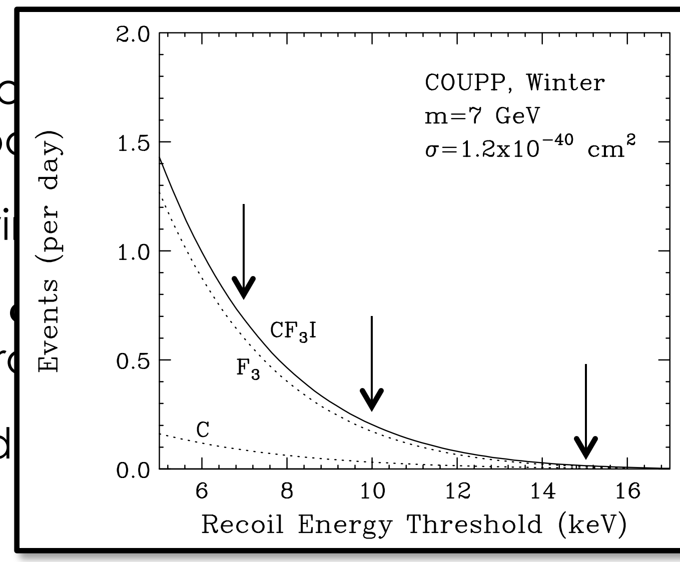


COUPP

- In the winter Aspen workshop, it was reported that COUPP has observed ~5-10 nuclear recoil candidate events in each of their low threshold runs (7 and 10 keV)

- More recently, they have been running with a 15 keV threshold

- If a much smaller rate is observed at 15 keV, this could be consistent with a ~5-10 GeV WIMP with a ~10^{-40} cm^2 cross section

Searches For Gamma Rays From Dark Matter Annihilations With Fermi

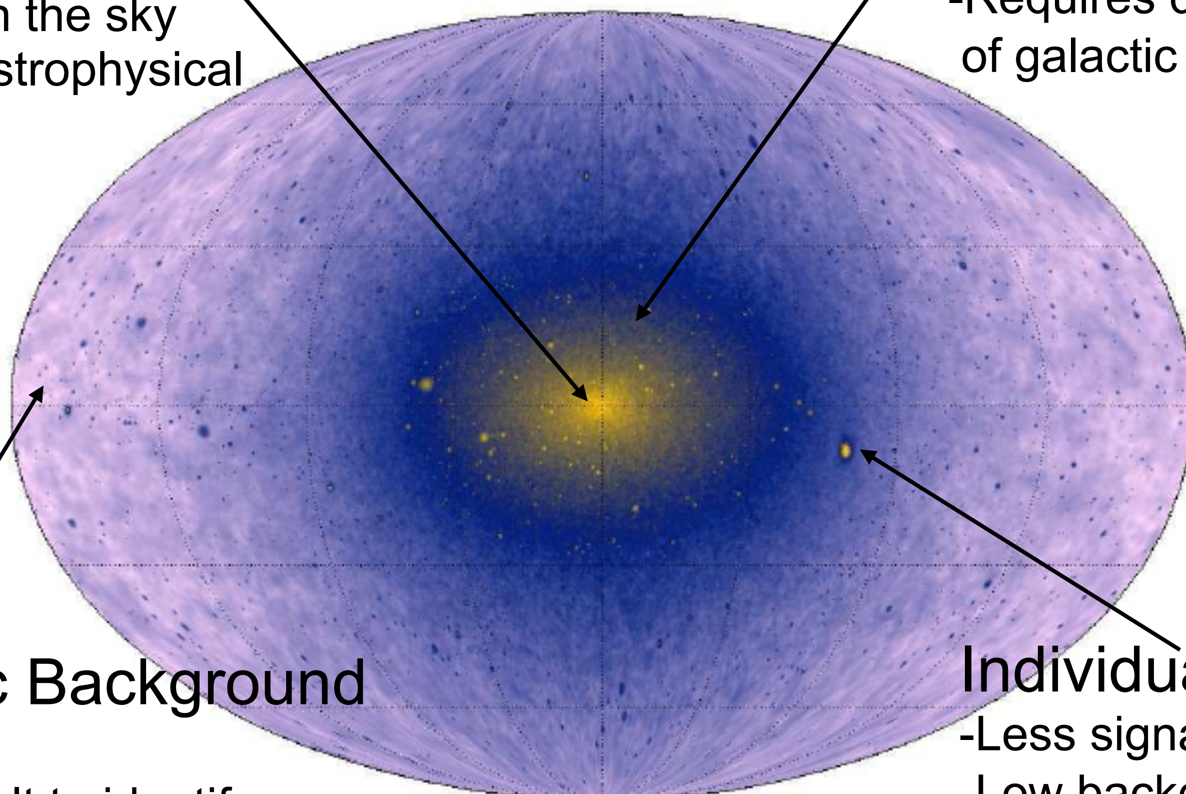
- The Fermi Gamma Ray Space Telescope has been collecting data for more than two and a half years

- In August 2009, their first year data became publicly available

- Fermi's Large Area Telescope (LAT) possesses superior effective area (~7000-8000 cm^2), angular resolution (sub-degree), and energy resolution (~10%) than its predecessor EGRET

- Unlike ground based gamma ray telescopes, Fermi observes the entire sky, and can study low energy gamma rays (down to ~300 MeV)

Where To Look For Dark Matter With Fermi?



The Galactic Center
-Brightest spot in the sky
-Considerable astrophysical backgrounds

The Galactic Halo
-High statistics
-Requires detailed model of galactic backgrounds

Extragalactic Background
-High statistics
-potentially difficult to identify

Individual Subhalos
-Less signal
-Low backgrounds

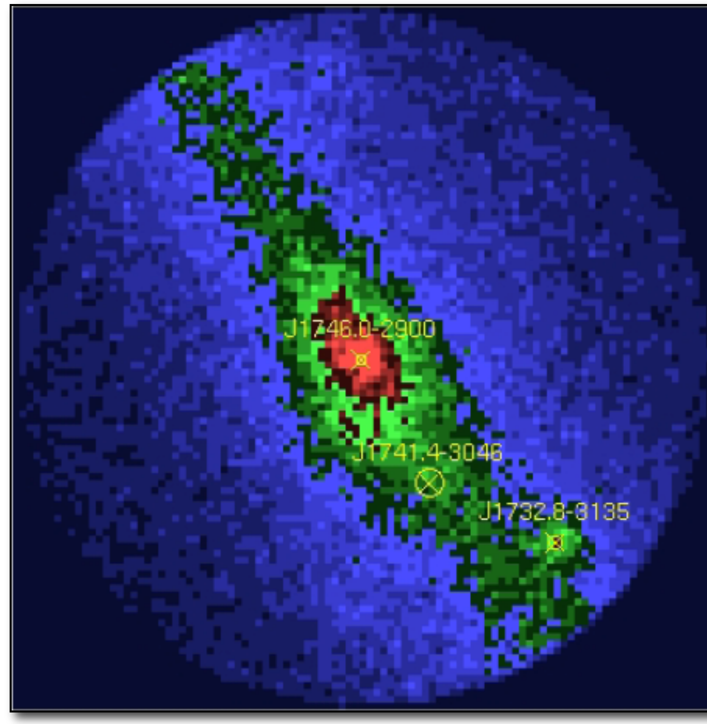
Dark Matter In The Galactic Center Region

- The region surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood

- This does not, however, necessarily make searches for dark matter in this region intractable

- The signal from dark matter annihilation is large in most benchmark models (typically hundreds of events per year)

- To separate dark matter annihilation products from backgrounds, we must focus on the distinct observational features of these components



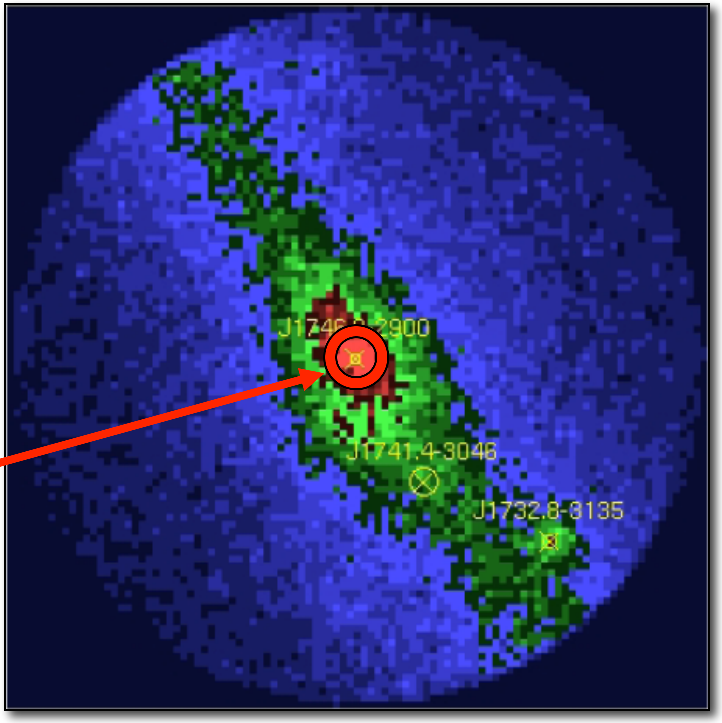
Dark Matter In The Galactic Center Region

The characteristics of a signal from dark matter annihilations:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\mathrm{los}} \rho^2(r)\mathrm{d}l$$

1) Signal highly concentrated around the Galactic Center (but not entirely point-like)

2) Distinctive "bump-like" spectral feature



Astrophysical Backgrounds In The Galactic Center Region

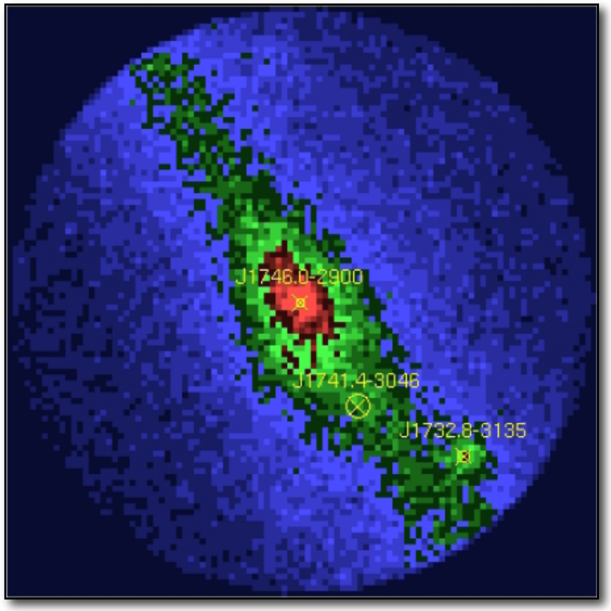
Known backgrounds of gamma rays from Inner Galaxy include:

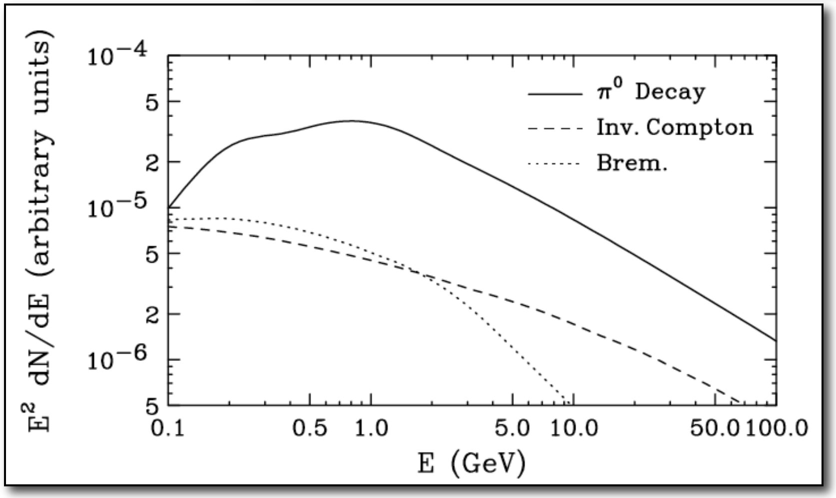
1) Pion decay gamma rays from cosmic ray proton interactions with gas ($p+p \to p+p+\pi^0$)

2) Inverse Compton scattering of cosmic ray electrons with radiation fields

3) Bremsstrahlung

4) Point sources (pulsars, supernova remnants, the supermassive black hole)



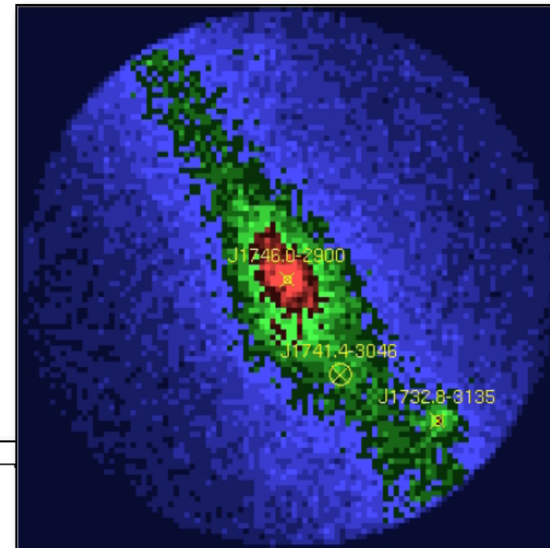


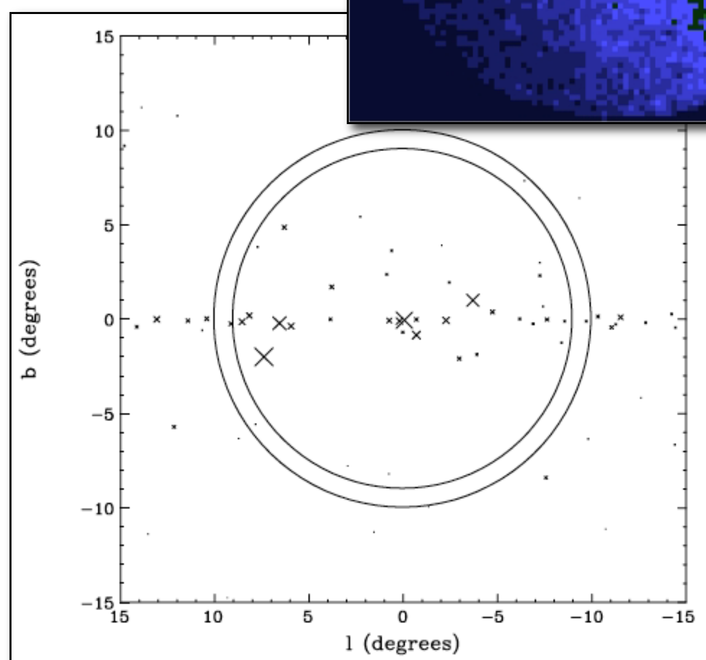
Astrophysical Backgrounds In The Galactic Center Region

- Much of the emission is concentrated along the disk, but a spherically symmetric component (associated with the Galactic Bulge) is also to be expected

- The Fermi First Source Catalog contains 69 point sources in the inner +/-15° of the Milky Way

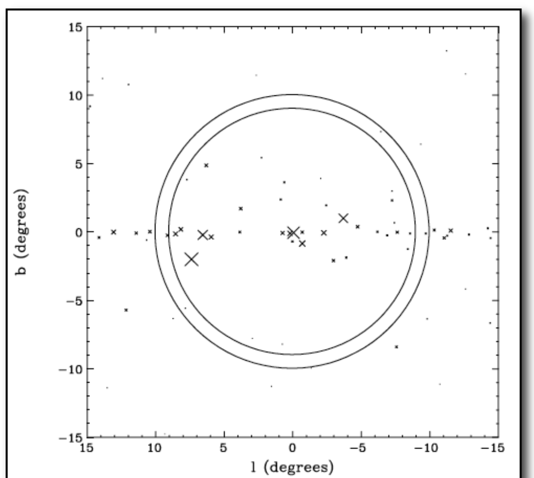
- Build a background model with a morphology of disk+bulge+known point sources

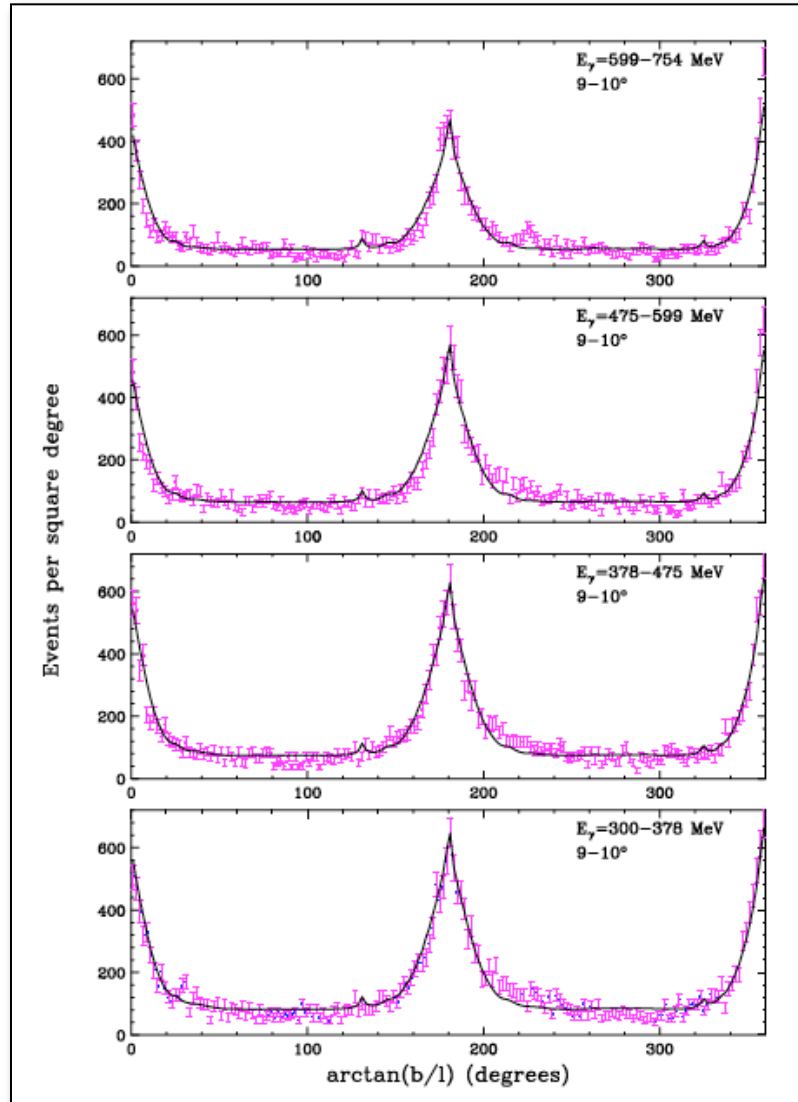




Astrophysical Backgrounds In The Galactic Center Region

- Fit one energy bin at a time, and one angular range around the Galactic Center
(no assumptions about spectral shape, or radial dependence)
- Fit to intensity of the disk (allow to vary along the disk), width of the disk (gaussian), intensity of the flat (spherically symmetric) component
- Include point sources, but do not float
- Provides a very good description of the overall features of the observed emission (between ~2-10° from the Galactic Center)





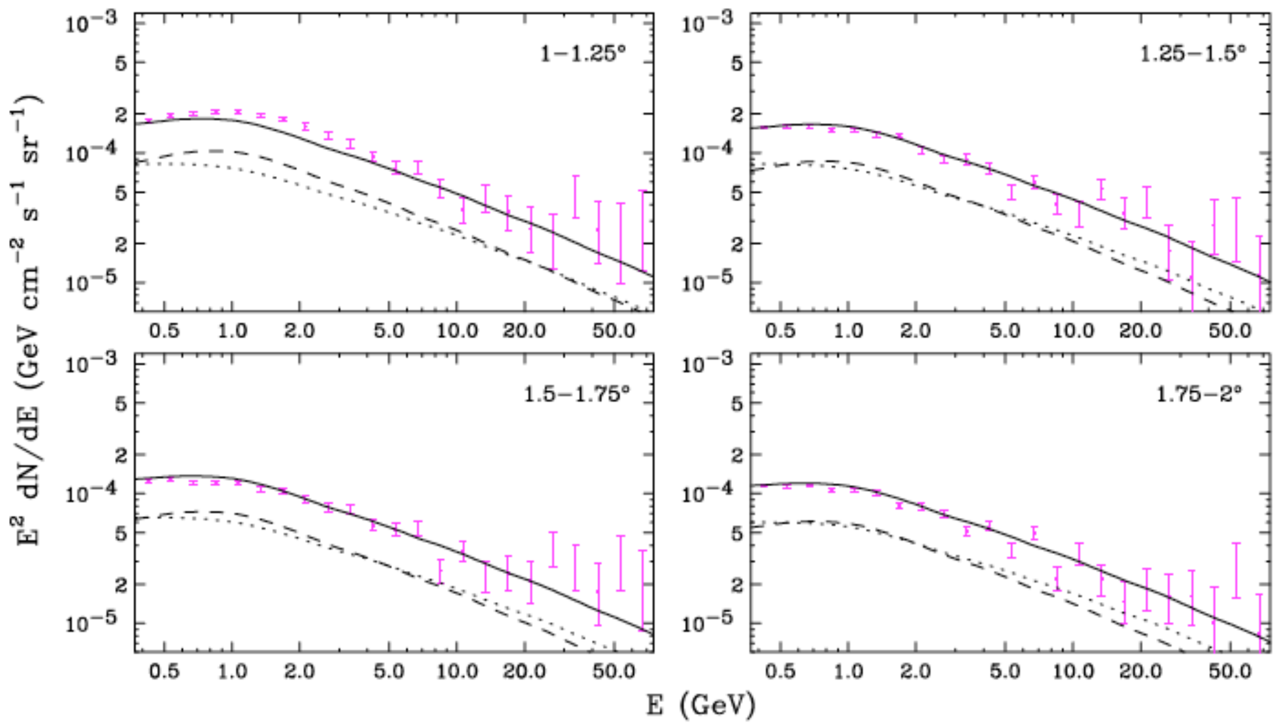
Dan Hooper - *Light WIMPs!*

The Inner Two Degrees Around The Galactic Center

- If the Fermi data contains a signal from dark matter annihilations in the Galactic Center, we should expect to see departures from the background model within the inner ~1 degree
- The key will be to observe both the morphological and spectral transitions in the data

Dashed=disk
Dotted=bulge
Solid=disk+bulge

- Between 1 and 10° from the GC, our background model does very well



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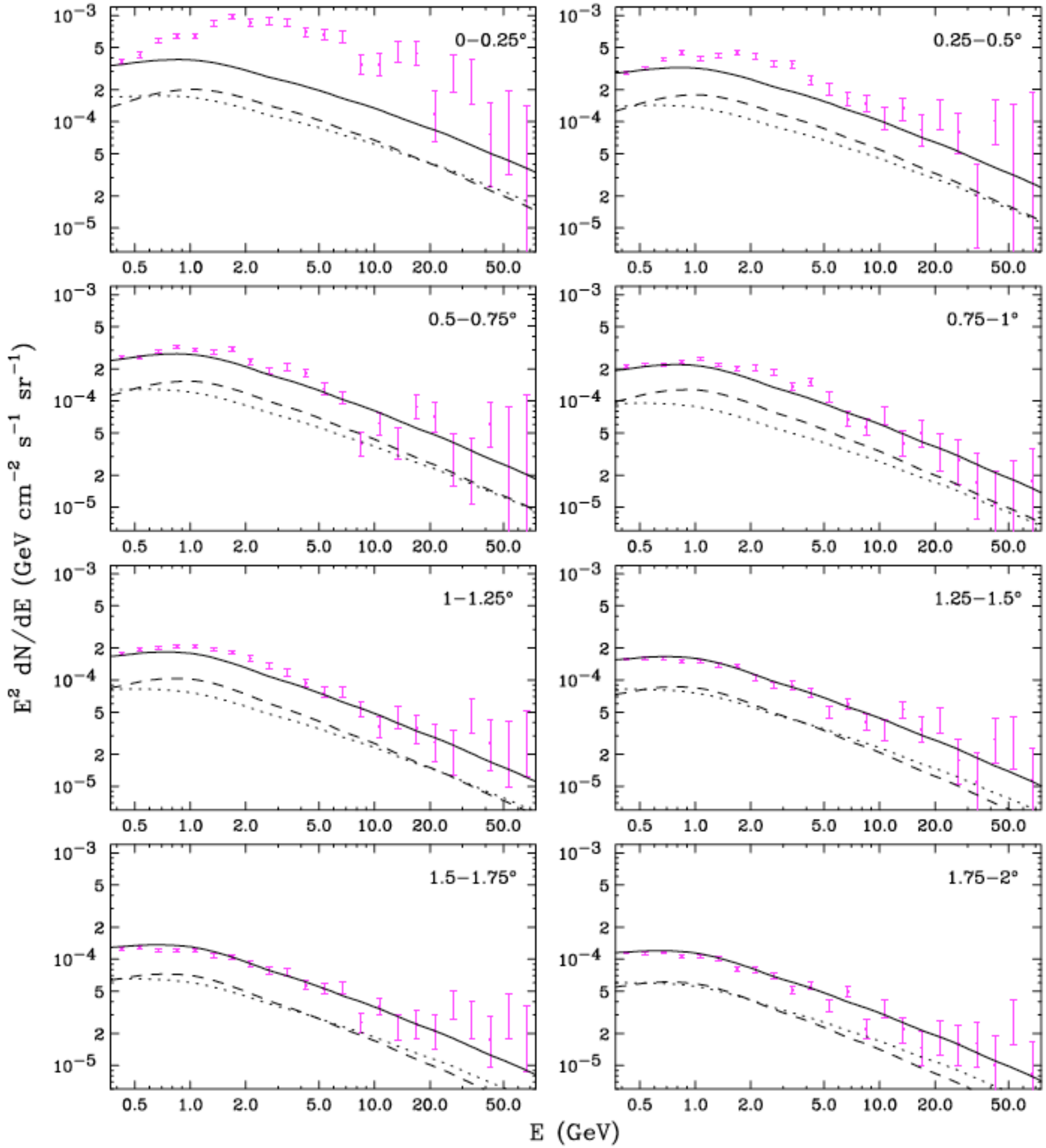
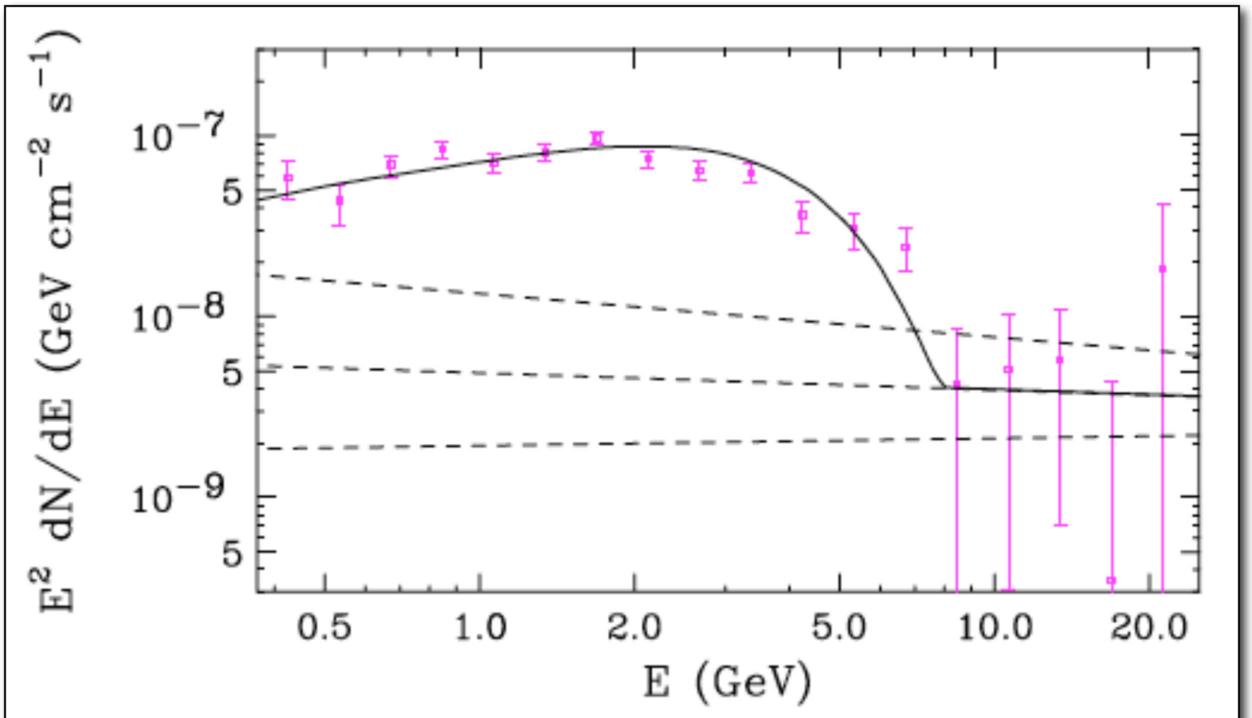
- Between 1 and 10° from the GC, our background model does very well
- Inside of ~0.5°, backgrounds utterly fail to describe the data
- A new component is clearly present in this inner region, with a spectrum peaking at ~1-4 GeV



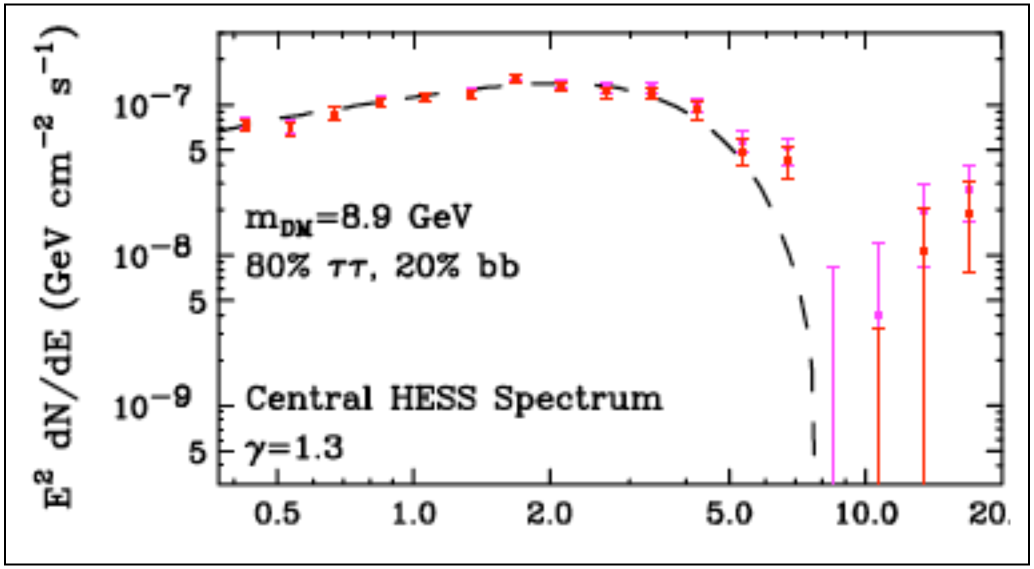
The Spectrum Of The Excess Emission

- We have been able to cleanly extract the spectrum of the central emission (not disk or bulge)
- Emission peaks around 1 to 4 GeV
- No statistically significant excess above ~6-7 GeV



The Dark Matter Interpretation

- The spectral shape of the excess can be well fit by a dark matter particle with a mass in the range of 7 to 10 GeV (*similar to that required by CoGeNT and DAMA*), annihilating primarily to $\tau^+\tau^-$ (possibly among other leptons)



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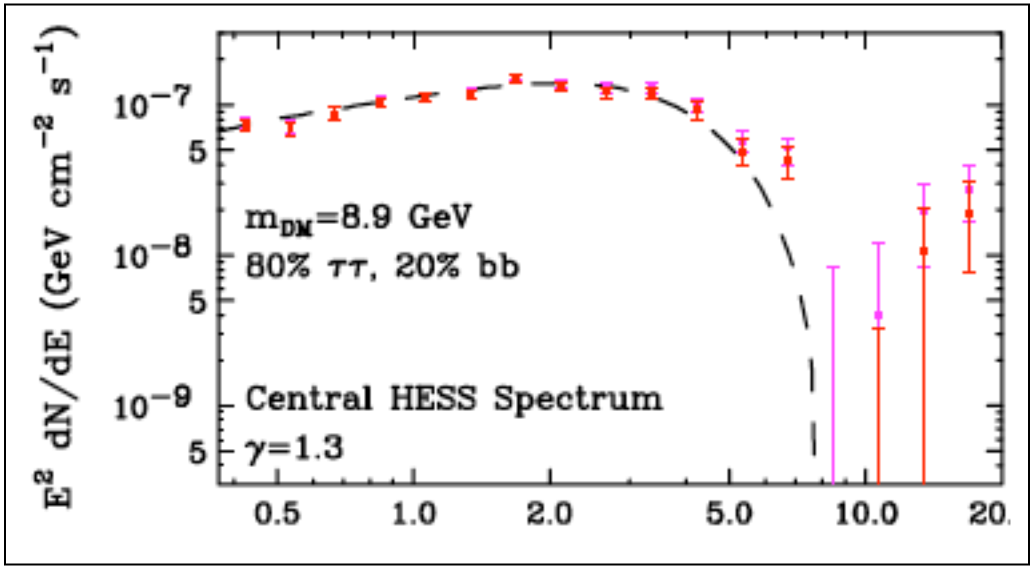

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- The angular distribution of the signal is well fit by a flux distribution that scales with $r^{-\alpha}$, with α=2.36 to 2.66; if interpreted as dark matter, this implied an inner profile $\rho(r) \sim r^{-\gamma}$, with γ=1.18 to 1.33 *(in good agreement with simulations*)

- The normalization of the signal requires the dark matter to have an annihilation cross section (to $\tau^+\tau^-$ and hadronic channels) of σv = 4.6x10^{-27} to 5.3x10^{-26} cm^3/s (*in agreement with the value of 3x10^{-26} cm^3/s predicted for a simple thermal relic*)

Other Interpretations?

Challenges:

- Very concentrated, but not point-like, emission (scales with roughly $r^{-2.5}$)
- Hard and peaked spectral shape ($dN/dE \sim E^{-1}$)

Other Interpretations?

Unresolved Point Sources?

Perhaps a population of ~50 or more unresolved points sources distributed throughout the inner tens of parsecs of the Milky Way could produce the observed signal - millisecond pulsars, for example

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Two problems:

1) Why so many in the inner 20 pc, and so few at 100 pc?

-With typical pulsar kicks of 250-500 km/s, millisecond pulsars should escape the inner region of the galaxy, and be distributed no more steeply than r^{-2} (assuming that *none* are created outside of the inner tens of parsecs)

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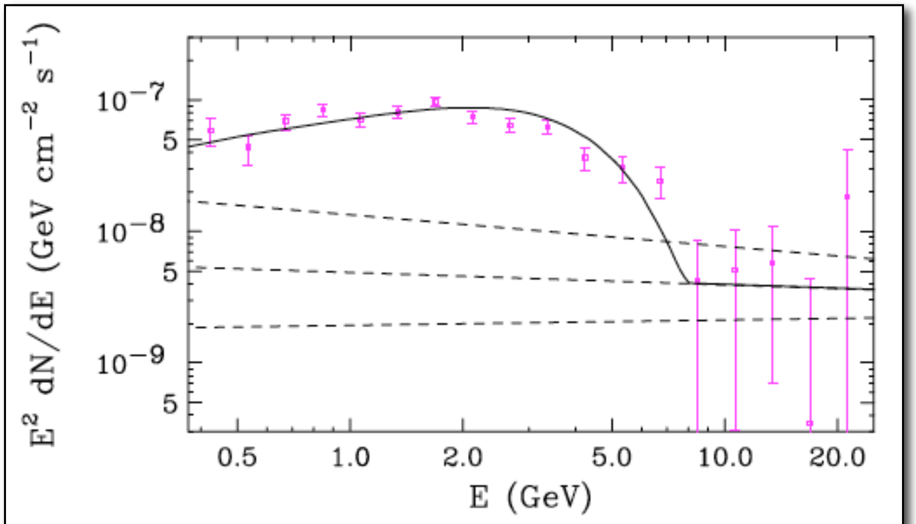
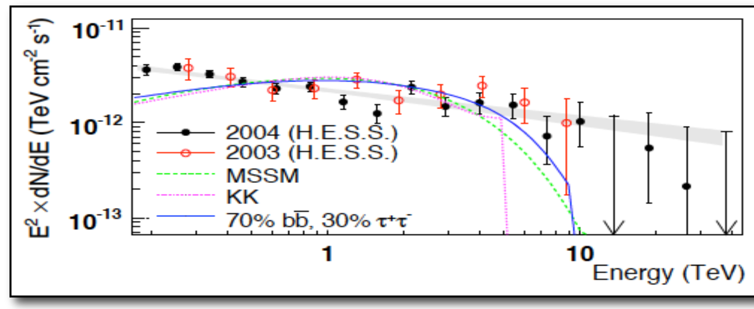
2) The spectral shape of gamma rays from pulsars has been measured (46 are in the FGST's catalog), and is not consistent with the spectrum observed from the Galactic Center (a different population or class of pulsars that those observed by Fermi?)

Other Interpretations?

Confusion with the Galactic Center's Supermassive Black Hole?

- Above ~8 GeV, the observed spectrum agrees very well with an extrapolation of the power-law emission reported by HESS (at ~200 GeV to ~20 TeV)





- Much of the central emission observed by FGST could potentially originate from the SMBH, but this would require a dramatic departure from the power-law observed at higher energies

- The data also significantly prefers an extended source for the peaked emission (but this is difficult to state in a way that is independent of the details of the PSF)

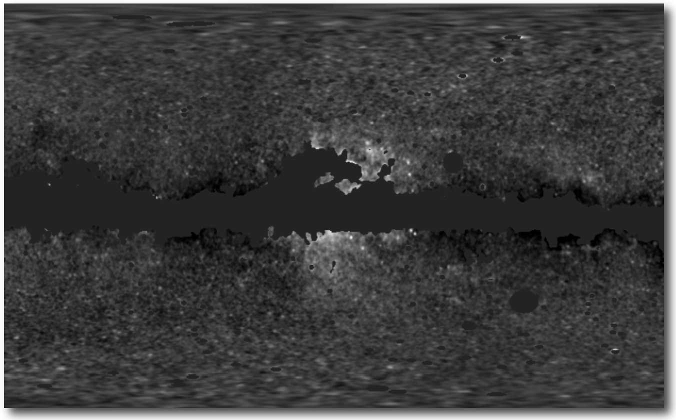
- I eagerly await further study of this issue by the Fermi Collaboration

Other Signatures of Light WIMP Annihilation in the Inner Milky Way?

If dark matter annihilations are generating the gamma ray emission observed from the Galactic Center, where else in the sky, and in what other channels, might signals of this appear?

Other Signatures of Light WIMP Annihilation in the Inner Milky Way?

- For years, it has been argued that the WMAP data contains an excess of synchrotron emission from the inner ~20° around the Galactic Center, and that this cannot be explained by known astrophysical mechanisms
- Previous studies have shown that this emission could be accounted for electrons produced in dark matter annihilations



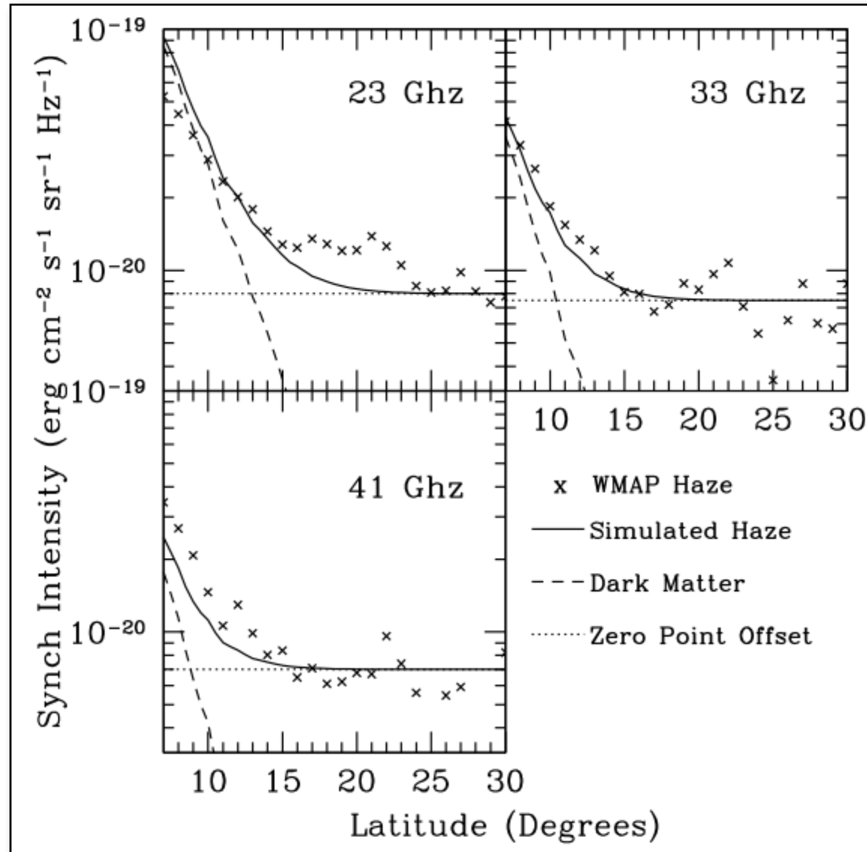
WMAP Haze (22 GHz)

Finkbeiner, astro-ph/0409027;
Hooper, Finkbeiner, Dobler, PRD (2007);
Dobler, Finkbeiner, ApJ (2008)

Synchrotron Emission and The WMAP Haze

- Using the halo profile, mass, annihilation cross section and annihilation channels determined by the Fermi GC data, we proceed to calculate the corresponding synchrotron spectrum and distribution
- Set B-field model to obtain the spectrum and angular profile observed by WMAP (almost no additional freedom)
- The resulting synchrotron intensity is forced to be very close to that observed

A dark matter interpretation of the Galactic Center gamma rays (almost) automatically generates the WMAP Haze

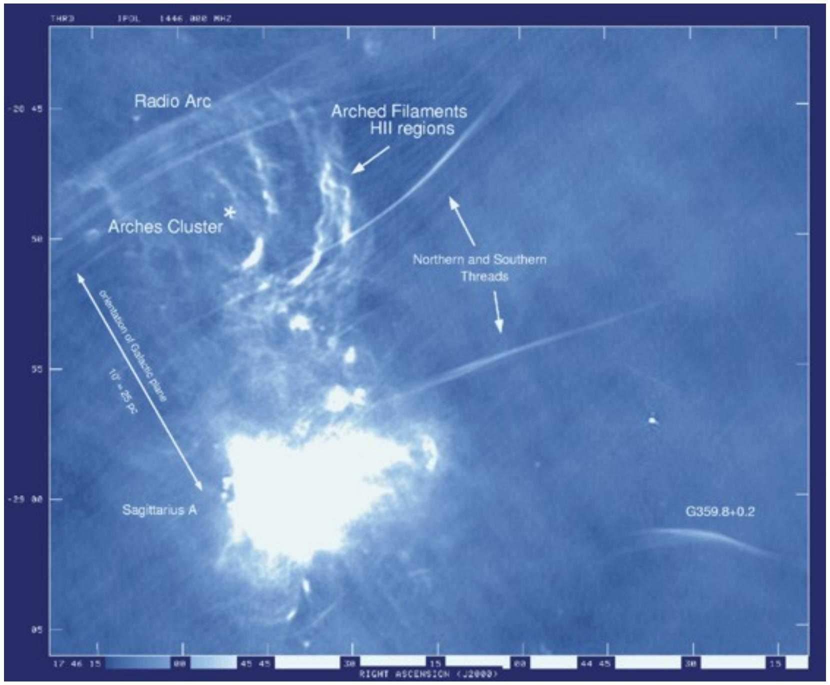


Annihilations to e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
B~10 μG in haze region

D. Hooper and Tim Linden, arXiv:1011.4520

Non-Thermal Radio Filaments

- Radio filaments are long (~40 pc) and thin (~1 pc) structures with extremely hard and polarized radio spectra, located 10-200 pc from the Galactic Center
- Observations imply very strong (~100 μG) and highly ordered magnetic fields
- It has been a long-standing challenge to explain the synchrotron spectra from these objects



Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493

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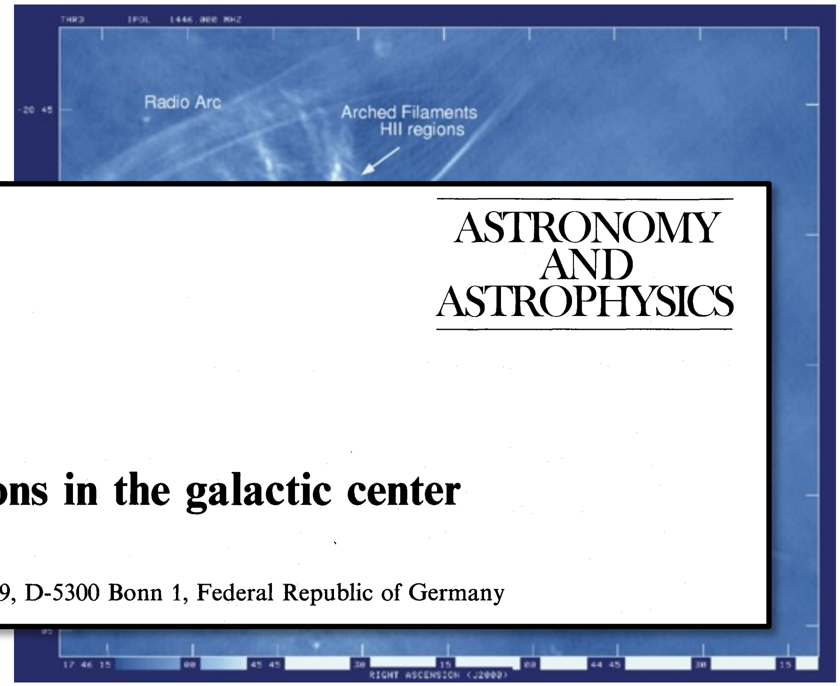


Astron. Astrophys. 200, L9–L12 (1988)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

H. Lesch*, R. Schlickeiser, and A. Crusius

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

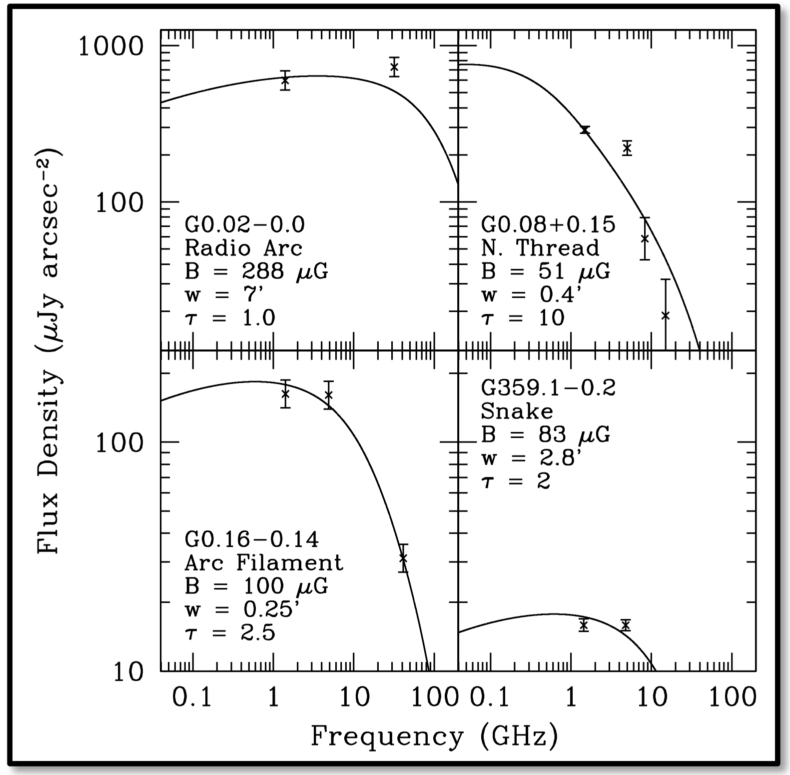
- Since the late 1980's, modeling of NRFs has found that they must contain a nearly mono-energetic spectrum of electrons, with an energy of ~7 GeV

- Very difficult to explain with astrophysics, but automatic for a 5-10 GeV WIMP annihilating to leptons

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493

Non-Thermal Radio Filaments

- We find that the handful of best-measured NRFs have spectra that can be easily explained by annihilating dark matter

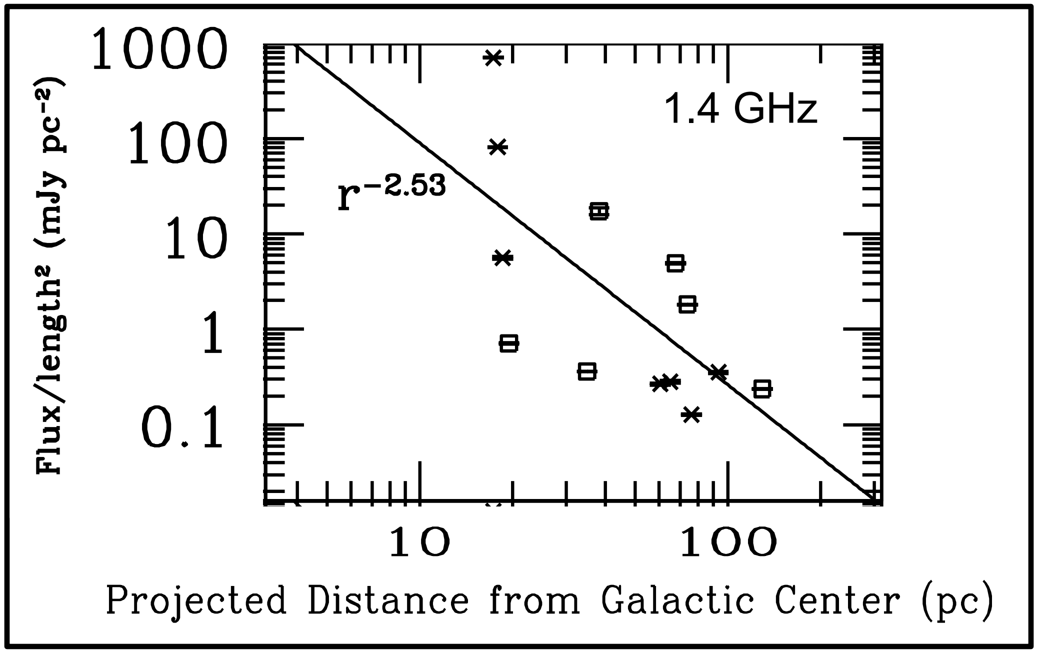


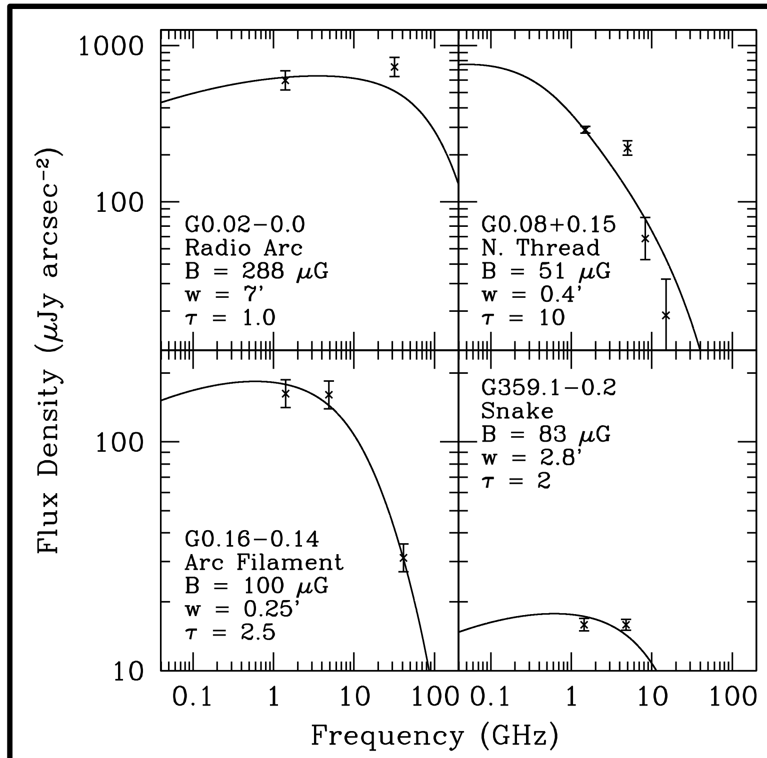
Annihilations to e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
m_X=8 GeV, σv=3x10^{-26} cm^3/s

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493

Non-Thermal Radio Filaments

- We find that the handful of best-measured NRFs have spectra that can be easily explained by annihilating dark matter
- We also observe a correlation between brightness and distance from the Galactic Center; in a dark matter interpretation, this corresponds to roughly $\rho \sim r^{-1.25}$





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- Although evidence for light WIMPs has appeared in a variety of experiments (CoGeNT, DAMA, Fermi, WMAP, CRESST), the case for this interpretation is not yet incontrovertible

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- Other results to bear include:
  - -Details of the CRESST excess (TAUP 2012)
  - -Fermi collaboration study of the Galactic Center
  - -Planck's view of the WMAP haze (2013)
  - -Low and high threshold results from COUPP (TAUP 2012)
  - -CDMS modulation analysis
  - -Further studies of radio filaments
  - -Southern hemisphere experiments (DM-Ice)